Jupiter's Synchrotron Radiation: Observed Variations Before, During, and After the Impacts of Comet SL–9

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Responding to predictions that periodic comet Shoemaker-Levy-9 (SL–9) would impact Jupiter in July of 1994, radio astronomers worldwide carried out a campaign to observe and monitor the synchrotron emission from the Jovian radiation belts. Substantial increases in the planet's synchrotron emission were reported by several research teams (Ref. 1) during the week of July 16–23 at numerous wavelengths spanning the decimetric spectrum.

The NASA/JPL Jupiter Patrol, a long-term radio astronomy monitoring program begun in 1971 (Ref. 2), participated in the campaign to monitor the effects of the SL–9 impacts. The Jupiter Patrol observations are made at 2295 MHz (13 cm wavelength) using the large filled-aperture antennas of NASA's Deep Space Network (DSN). The patrol data clearly show that the intensity of Jupiter's microwave radio emission varies smoothly +/-15 percent over timescales of years. While short-term variations with timescales of a few days have been reported in the past, none have ever been confirmed; at least not until the impacts of Shoemaker-Levy-9.

The primary source of Jupiter's microwave radio emission at frequencies below ~6000 MHz is synchrotron radiation from electrons with relativistic energies, i.e., their velocity is near the speed of light. The negatively charged electrons radiate as they spiral up and down the magnetic field lines of the planet's inner magnetosphere. The intensity of the emission depends on the orientation and strength of the magnetic field, as well as the number and energy distribution of the relativistic electrons. At frequencies above ~6000 MHz, thermal radiation from the deep Jovian atmosphere emerges as the primary source of microwave radio emission.

A radio brightness map of the synchrotron emission measured with the Very Large Array (VLA) (Ref. 3) is shown in Figure 1. Note that the emission is concentrated near the magnetic equator with secondary brightening at low latitudes above and below the equatorial plane. The maximum brightness occurs near 1.5 Jovian radii (R_J) from the planet and very little microwave emission is observed beyond 3 R_J. Single-dish radio telescopes, like those used for the Jupiter Patrol, measure the spatially-averaged intensity of the synchrotron emission, because the solid angle of the antenna beam is typically much larger than the angular dimensions of the emitting region.

The results of the Jupiter Patrol observations from 1994 to 1997 are shown in Figure 2. The data points represent the peak intensity of Jupiter measured at Goldstone primarily with the 34-m antenna, located at the DSS 13 research and development station. The 70-m antenna was used for approximately 10 percent of the observations. The data show that the synchrotron flux at 13-cm increased 27 percent during the week of the impacts in July 1994 and was followed by a steady decline that began in August and continued throughout 1995.

The dotted curve in Figure 2 is an estimate of the baseline made by fitting a second order polynomial to the data taken before July 15, 1994 and after September 1995. The downward sloping baseline is consistent with the long-term decline in Jupiter's synchrotron emission that began in 1991–92, and may be related to the current minimum in the 11-year cycle of sunspots and

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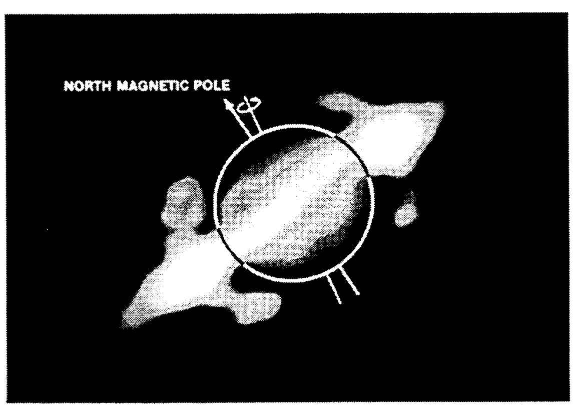

FIGURE 1. A RADIO BRIGHTNESS MAP OF JUPITER'S INNER MAGNETOSPHERE, TAKEN AT 1400 MHZ WITH THE 27-ELEMENT NRAO VERY LARGE ARRAY IN NEW MEXICO.

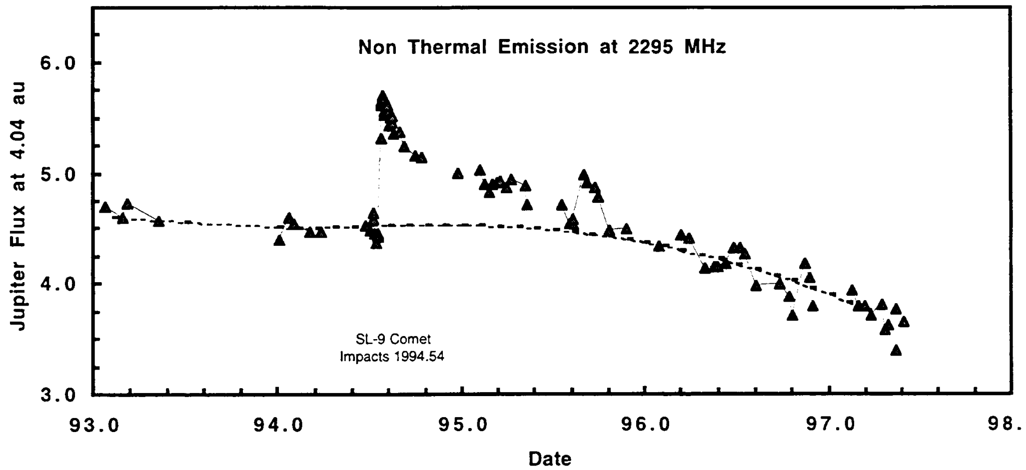

FIGURE 2. THE INTENSITY OF JUPITER'S SYNCHROTRON EMISSION OBSERVED AT 2295 MHz.

solar magnetic storms. Figure 3 is a plot of the data after the baseline is subtracted. The exponential curve is given by e^(-70/t), where t is the number of days since July 16, 1994.

The rapid outburst that began the first day of the week-long series of impacts was accompanied by dramatic changes in the radio maps produced from observations at the VLA, as well as radio astronomy observatories in Australia and Europe. The results were surprising because nearly all theorists had predicted that cometary dust would scatter and deplete the energetic electrons and the net effect would be a decrease, not an increase, in the synchrotron radio emission.

The Jupiter Patrol observations revealed a second, unexpected result. The data in Figure 3 seem to indicate that a second outburst with a peak increase of approximately 10 percent was observed in late August of 1995. There is no reason to assume this outburst is related to the much stronger SL–9 event observed 15 months earlier. The Jupiter Patrol observations have been intensified to search for other short-term outbursts that would confirm their existence and reveal new information about the physics of the inner magnetosphere.

The surprising observational results that followed the SL–9 impacts have spawned new theories, as teams of scientists compete to explain the data. Two of the leading candidate processes are: (a) high-speed shock waves that temporarily

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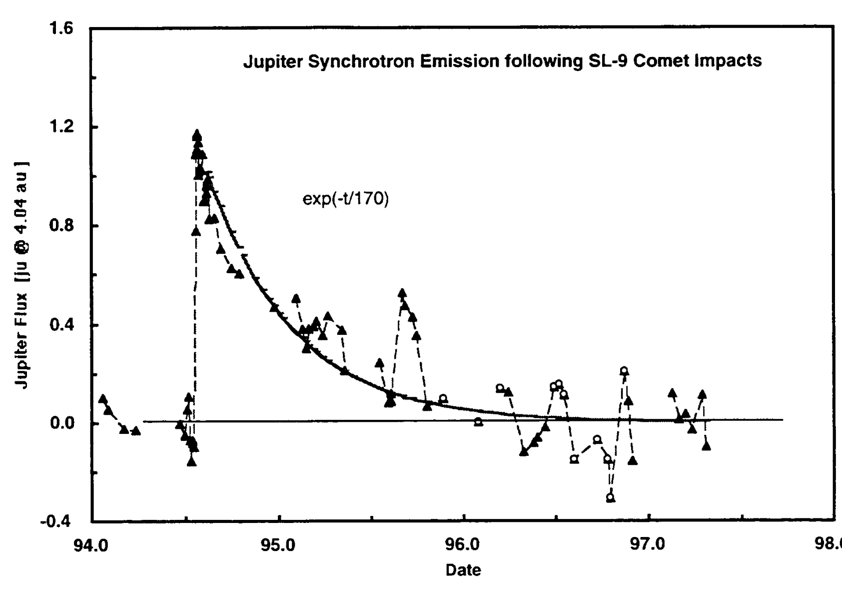

FIGURE 3. DATA FROM FIGURE 2, WITH BASELINE REMOVED, SHOWING THE RAPID INCREASE AND THE SLOW DECAY FOLLOWING THE IMPACTS OF COMET-SHOEMAKER-LEVY-9, IN JULY 1994.

or developed for space use. It includes the physical layer (RF and Modulation) where important work has been done to establish a common link design control table; a program for optimizing modulation indices for simultaneous telemetry, command, and ranging; and development of filtering techniques for reducing the occupied bandwidth of emissions by as much as 10 times. It includes data link layer protocols (error correction coding, framing, randomization, and synchronization), and a rudimentary network layer (Packetization). Current work includes developing a new standard for Turbo Coding that will improve the link quality in very-low-SNR environments. This is needed because advanced data systems operate in a data-driven mode where errors are simply not acceptable.

Other work, being developed jointly with DOD, uses these lower layer protocols on which to build an upper layer set to provide end-to-end reliable communications using Transport, Security, and File Transfer protocols. These layers are based on the corresponding traditional internet protocols, modified as necessary for the space environment.

A standard for lossless data compression that uses source encoding has been developed that will improve the throughput of the space link without propagating errors in the end user's data reconstruction process. A time code standard has also been developed, which reduced to four the proliferation of 53 different time codes that were used by JPL missions in the past.

Information Interchange Standards

This area is developing standards and tools for improving the interpretation of space data in a permanent way; useful during a project and after it has ended, when its knowledgeable people are gone. Included are standards for formatting space data sets, languages and formats for describing the formats of the data sets, and dictionaries for describing the contents of the data sets (e.g., measurement names, units, DN-to-EU conversions, etc.) In addition, a distributed, hierarchical system for registering the languages, formats, and dictionaries with a control authority has been set up in NASA and several other agencies, and a network linking these control authorities to freely access the distributed data base is being developed. A toolkit for working with the Standard Formatted Data Units is also available. Current work includes developing Archiving Standards for space data.

Mission Services

With the new NASA Space Operations contract coming soon, it is important to define the standard services that NASA will provide its customers. Today, nearly each customer negotiates a different and uniquely defined set of services to receive from NASA, because there are no standards. These deal with the delivery of Telemetry data, handling of Telecommand data, scheduling, tracking and orbit determination, time correlation, and so on.

TMOD is becoming a provider of standard operational services to reduce the costs of doing business (up to now, providing customized solutions) with our customers. To be able to provide these common services requires the establishment of certain standards for the operation of space and ground data systems. The establishment of these standards for routine operations will enhance interoperability among mission operations, ground support services, and agencies, and encourages product competition from smaller manufacturers, and lowered costs when operations are outsourced.

The secret of a well-engineered service standard is to allow needed flexibility to serve the majority of customers while limits are put on the customization (or variety) of services to constrain costs. To the extent possible, these services rely on the underlying features of the existing CCSDS Recommendations (such as Packet Telemetry, Telemetry Channel Coding, and Standard Formatted Data Units) for handling and accountability. Standard Services are being developed locally at JPL by TMOD Level-0 System Engineering, and the standards program is linking this work to other NASA centers and space agencies through the CCSDS.

The first standard Service definitions are nearly ready: *Return-All-Frames Service* for telemetry, and *CLTU Service* for telecommand. Others will follow soon, and as more agencies and projects adopt these standards, it becomes easier to interface with agencies, NASA centers, and projects.

Application Engineering

At JPL, the standards program also promotes the notion of Application Engineering, which we view as a help to the first-time implementor of the standard to interpret and apply it properly. Our CCSDS experts are available to answer questions and to provide background information on the program, on the standard itself, or possibly to help with identification and selection of conforming CCSDS products on the market.

In addition, periodic "Industry Days" are held for U.S. industry to keep it abreast of the latest developments in the program, and for the program to learn what new standards are wanted by industry.

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